SHOULDER UPLIFT OF THE WESTERN GHATS PASSIVE MARGIN, INDIA: A DENUDATIONAL MODEL

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ABSTRACT

The paper presents a denudational rift flank uplift model of the Western Ghats of Karnataka, India. The Cenozoic denudation of the Deccan plateau was constrained by relative dating of regional planation surface levels, in combination with preliminary apatite fission track results. The denudational history of the Western Ghats escarpment coastal foreland was constrained both by onshore fission track and offshore sediment data. Methods are briefly described. Results were used as reference data to elaborate a computer simulation model of both flexural rift flank upwarp and escarpment retreat from the K/T boundary to the present. Depending on the assumptions concerning the attributes of the thin elastic lithospheric sheet (infinite or semi-infinite), the shape and elevation of the initial Deccan topography (flat-lying, or affected by lithospheric updoming due to the Reunion mantle plume) and the position of the continental divide upon rifting, the flexural response to denudational unloading is shown to yield either a concave-up flexure of the Dharwar craton, or a convex, monoclinal downwarp of the margin. The relative merits of each model are discussed in the light of auxiliary field evidence, particularly from the neighbouring Deccan traps. However, the diverse assumptions on boundary conditions fail to entirely avoid geomorphological equifinality. © 1998 John Wiley & Sons, Ltd.

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INTRODUCTION AND STUDY AREA

Geodynamic studies of rifted margins have recently contributed to shift the long-standing emphasis from basin analysis towards an understanding of the onshore landscape morphology. High-elevation passive margins, by contrast with low-elevation margins (Gilchrist and Summerfield, 1994), are characterized by (i) a major escarpment, facing the sea, (ii) a continental upland region on the backslope of the escarpment and (iii) a coastal foreland region, at the foot of the escarpment.

The Western Ghats, along the western margin of India (Figure 1), belong to the category of high-elevation rifted margins. The escarpment can be followed continuously between 20 and 8°N, regardless of structure and lithology, since rock formations encountered along-strike vary from 65 Ma Deccan flood basalts in the north to Pan-African granulites in the south, via 2.5 Ga granite–greenstone terrain in the Dharwar craton (Figure 1).

The mean escarpment profile, which was computed from an ETOPO 5 digital elevation database by strike-averaging pixel stripes between 12 and 16°N, reaches a mean of 720 m in the region of interest – the crystalline Dharwar craton. An elevation profile computed in this manner is not suitable for highlighting actual planation levels since the resolution of ETOPO (one spot elevation value for a pixel of $5' \times 5'$) is apt to miss topographic details which constitute important clues to landscape development; however, the resolution of the flexural model, which merely aims to describe the macroscale morphology of the Western Ghats margin, is not expected to reveal significant resolution discrepancies with the level of information given by the digital profile.

Geomorphologists and geophysicists have a common interest in explaining the patterns of first-order topography, and methods pertaining to both disciplines can be combined to some advantage if compatible data are available. While the subsidence of passive margin offshore basins can be explained by fairly unchallenged

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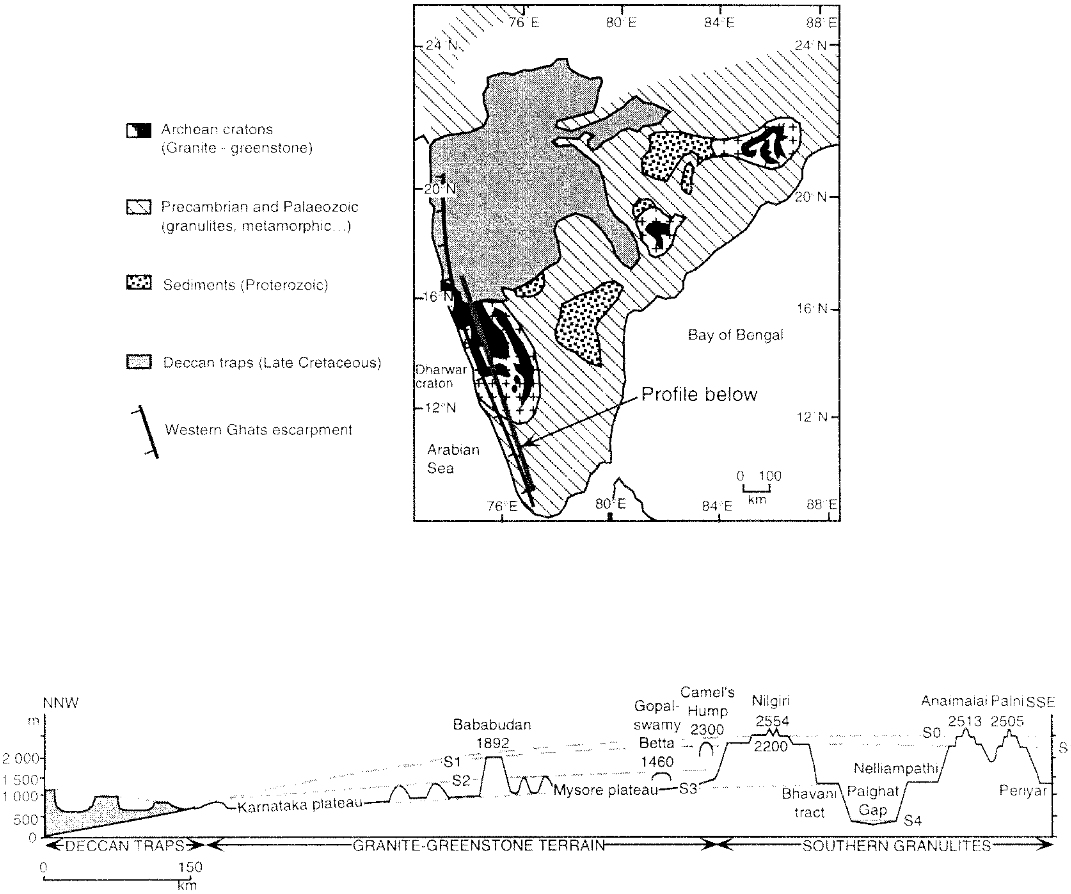

Figure 1. Geological location map and proposed palaeosurface profiles (schematic). S1 (Cretaceous palaeosurface) and S2 (Intermediate, Tertiary surface) show southward increase in available relief due to flexural upwarp. Note undulating surface (Widdowson, 1997) of Deccan lava. Palaeosurface reconstruction S0 to S4 is tentative and partly discussed in Gunnell (1997)

mechanical and thermal processes, the onshore mechanisms of shoulder uplift remain more controversial. No single geophysical model that the authors are aware of regarding the entire Western Ghats has been devised that might simultaneously explain (i) the observed escarpment relief, (ii) the length and continuity of the rift flank, (iii) the wavelength in cross-section of the rim bulge and, (iv) the persistence of the uplift over timescales greater than the thermal decay constant of a lithospheric slab heated by a mantle plume (i.e. greater than *c.* 60 Ma).

Reviews of the chief mechanisms which are held responsible for passive margin uplift are explored in Allen and Allen (1990), Keen and Beaumont (1990) and Summerfield (1991a). Among the more likely candidates which might fulfil the four constraints listed above, magmatic underplating is often evoked for regions of flood basalt activity. Since at least the northern third of the Western Ghats is a volcanic passive margin, this mechanism deserves some consideration. The Western Ghats were separated from the Seychelles–Mascarene platform at *c.* 65 Ma at the same time as the Reunion hotspot plume activity was reaching its peak (Subrahmanyam *et al.*, 1995). Underplating involves crustal thickening by accretion and intrusion of gabbroic material at the base of the crust in a large igneous province, and is expected to contribute to 'permanent' plateau surface uplift from the fact that the material is slightly denser than the crust itself, but less dense than the underlying mantle. The net effect is to increase the buoyancy of the thickened crustal layer, with the result of raising the mean elevation of the continental surface relative to the geoid. It has been emphasized that the Deccan flood basalts may have involved a degree of underplating (Devey and Lightfoot, 1986), although the

exact proportion of melt which did not reach the surface as basalt is difficult to estimate in continental regions, whether by seismic reflection methods (Lister and Etheridge, 1989) or by geochemical budget calculations. The latter method (estimation of the mass of 'missing cumulates') was discussed by Cox (1980, 1993), who concluded that the minimum mass of underplated material for the Deccan traps was about 50 per cent of the amount of basalt on the surface. Assuming reasonable initial thicknesses of lava, in the order of *c.* 3 km, the 1·5 km of correlative underplating was expected to yield very modest amounts of surface uplift (*c.* 0·1 km).

If magmatic underplating was as restricted, in the volcanic region itself, as suggested by Cox, and even though continental basalt was reported on the sea floor off the coast of Kerala (Ramanathan, 1983; Backman *et al*., 1988), it remains to be ascertained that underplating was any more abundant below the Dharwar craton. Furthermore, the mean elevation of the volcanic stretch of the Western Ghats is lower than anywhere else on the crystalline basement further south. Gravity anomalies and Moho depth (Verma, 1991), as for many divergent passive margins, do not reveal significant crustal thickening underneath the Indian shoulder uplift. This differs from, for instance, the sheared margin of southeastern Africa, where mechanical stretching and associated thermal processes of uplift are unlikely contributing factors, but where the unusually thickened crust may be accounted for by a substantial Karoo underplate. This, then, would simultaneously explain the gravity anomaly pattern suggesting a thickened crust (Birot, 1982), the durable plateau uplift of the Drakensberg, its greater relief, and the considerably greater mean elevation of the southeast African highlands (local relief along much of the Western Ghats is less than the height of the base of the Karoo volcanic outcrops along the Drakensberg (Lageat, 1989)).

Lithospheric delamination models could also, in theory, explain rift flank uplift of continental margins and satisfy the four conditions enumerated above. Delamination involves uplift caused by wasting away of a subcrustal lithospheric keel of cold mantle, thereby increasing the buoyancy of the lithosphere and entailing plateau uplift. The 'eroded' mantle is colder than the ambient oceanic mantle found at the same depth on the edge of the continental mass, and is denser than the overlying crust. However, a recent study of medium wavelengh gravity anomalies across passive margins (Doin *et al*., 1996) suggests that delamination may in fact not contribute significantly, if at all, to surface uplift.

In view of the fact that, for the Indian margin, a reliance on internal geodynamic processes has so far failed to provide a unifying model supported by empirical evidence, the so far uncharted alternative was to explore the rôle of external geodynamic processes, namely denudation, in contributing to the observed shoulder morphology. It is indeed becoming more widely accepted that denudation over geological timescales can be a major mechanical factor of lithospheric unloading and uplift. The lithosphere responds by flexural rebound and, in favourable conditions, results in net surface uplift (Gunnell and Fleitout, 1998). The wavelength of the shoulder uplift depends on the flexural rigidity of the modelled elastic plate, and the amplitude of surface uplift will also depend on the respective rate and duration of denudation both on the backslope and on the face of the retreating rift escarpment. The main problem lies with the methods by which to quantify the two key parameters: the denudation rates (or lost section of terrain) and the flexural rigidity (or effective elastic thickness) of the modelled South Indian continental lithosphere.

Since the Archean Dharwar craton appears to fit the criteria of an elastic slab of cold and fractured but unfaulted lithosphere, the chosen segment of the Western Ghats studied in this paper is particularly suitable as a test for the hypotheses formulated above. The rationale followed here borrows from a current of previous attempts at modelling high-elevation rifted margins by emphasizing the role of denudation (Gilchrist and Summerfield, 1991, 1994; Ten Brink and Stern, 1992; Van der Beek, 1995), in the sense that it is constructed as a finite difference computer simulation model. However, it attempts to incorporate several additional geomorphological constraints: a preliminary correlation of land surfaces, backed up by apatite fission track thermochronology and sedimentological methods lead to a simple, denudation-driven flexural model of landscape evolution since the K/T boundary at *c.* 60 Ma.

PROCEDURE

In order to estimate the lost section, and therefore the load removed from the elastic plate over the defined 60 Ma

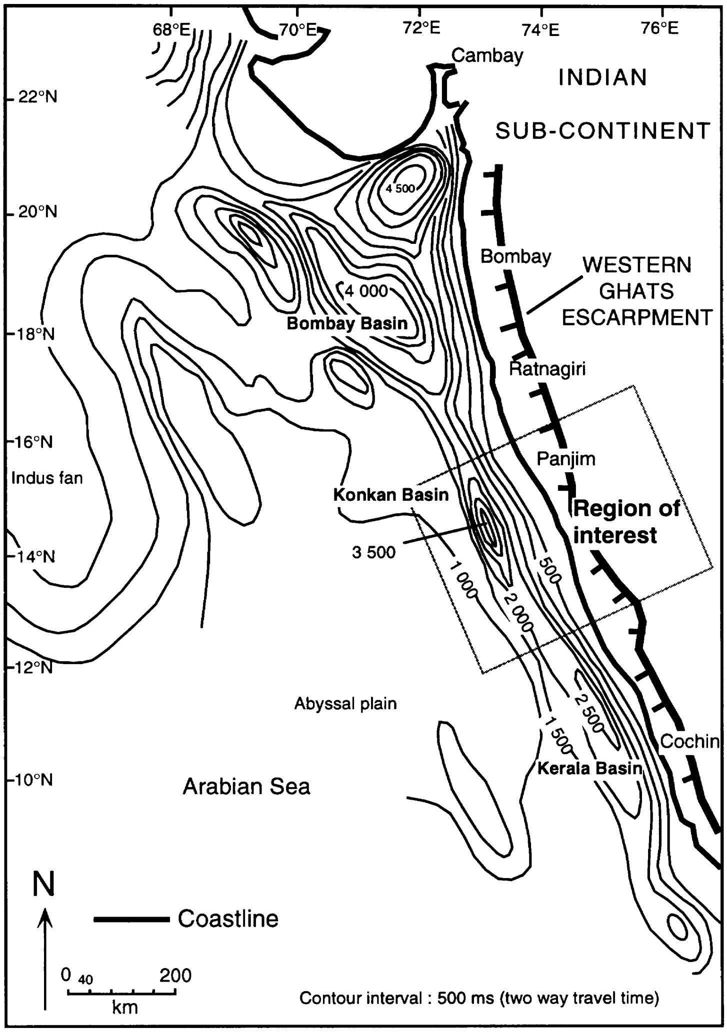

Figure 2. Isopach contour map for post-eruptive sediments of West Indian shelf basin (after Prasada Rao and Srivastava, 1984). Note greater thicknesses in the Bombay offshore basin, at least partly due to input from large rivers of the Narmada–Son rift system, and lower values off Cochin (Kerala basin). The volume of sediment was taken from the coastline to a 300 km offshore limit, which coincides with the Laccadive ridge. Two-way-time values were converted to sediment thickness values by considering that 1 s represents a standard 1 km of decompacted sediment thickness

period, it was both mathematically convenient and geographically relevant to dissociate the backslope of the Western Ghats from the Great Escarpment foreland region.

In continental interiors, a traditional way of estimating the lost section of terrain is to identify, wherever possible, different generations of stacked palaeosurfaces by tracing accordant summits, the highest level being the oldest. The difficulty in correlating land surfaces and rates of deformation in a crystalline basement region such as the Dharwar craton is compounded by the absence of datable sediments, which could bracket the identified levels. The Deccan flood basalts, which thin out onto the craton close to the 16th parallel (Figure 1), were used as a reference level. The Cretaceous cratonic palaeosurface upon which the volcanic load was emplaced at 65 Ma emerges at the basalt–basement contact. The Cretaceous palaeosurface can be tentatively extended across level-crested greenstone fold belts towards the south (Gunnell, 1997) in such a way that the summit-height envelope of the Karnataka uplands, namely the Bababudan and the Kudremukh greenstone massifs at elevations of *c.* 1950 m, can be assumed to derive from this pre-Deccan trap surface. Even further to

the south, it may be speculated that the Nilgiri and Palni highlands (Figure 1), which exhibit significant bevels at *c.* 2200 m, are remnants belonging to the same generation.

Below these residual surfaces, the current active surface lies around 900 m on the Mysore plateau. By this rule of thumb approach, we can hypothesize that, since the K/T boundary, a minimal crustal thickness of 1200 m has been removed on the backslope of the Western Ghats.

In the coastal region, the lost volume of rock due to post-Cretaceous erosion was estimated from offshore isopach and borehole data. Denudation of the foreland was simulated by giving the continent an assumed geometry at rifting and eroding it step-wise until the known offshore mass of sediment was attained. This procedure provided a way of estimating the load removed from the unstretched edge of the Deccan plateau and progressively redistributed over the stretched crust of the continental shelf. The main obstacle to achieving this exercise lies in the paucity of available well logs south of the Bombay offshore region (only two for the Konkan offshore region concerned). The document used for the present study was therefore the seismic thickness map of Prasada Rao and Srivastava (1984; Figure 2) which, if accurate, provided acceptable resolution for the purpose of the model.

The third method used to estimate the lost section was apatite fission track analysis. Seventy-five apatite samples were analysed (Gunnell *et al.*, in preparation) following IUGS recommendations (Hurford, 1990). Apatite fission track analysis is a low temperature thermochronological method, which consists in modelling the thermal history of apatite crystals from the pattern of nuclear fission tracks observed in the crystal lattice. Tracks in fluorapatite (the composition of the apatites used in this study) are preserved below the critical temperature of *c.* 110°C and accumulate over time. Hence, the density of tracks in a sample will reflect the length of time which this sample has spent between the 110°C isotherm and outcrop. If the geothermal gradient is known, and if it can be inferred that no thermal anomaly has disturbed the history of the samples by resetting the radiometric clock, then the cooling path of the apatites can be attributed to denudational processes. Whether active tectonic uplift, due to Earth interior processes, or passive lithospheric rebound, due to Earth surface processes such as denudational unloading, is responsible for the observed denudation, is neither self-evident nor immediately borne out by the apatite fission track record. The modelling exercise discussed in the next section will indeed show that it is a matter of interpretation to decide whether surface uplift is a result of tectonic uplift, isostatic rebound, or a combination of both.

In addition to the density of fission tracks in the sample, which gives an estimate of the apparent time each sample took to cool from the critical isotherm to the surface but is of little value on its own, the length distribution of tracks in each sample has to be taken into account. Fission tracks have a tendency to 'anneal' (i.e. segment and shorten) and eventually disappear when the apatite grains spend a certain length of time at temperatures between 60 and 110°C. The disappearance of a fraction of the track population by this process bears on the overall density and therefore on the 'age' of the sample, which can only then be considered as *apparent* and requires to be corrected. The analytical principles of the fission track technique can be found in Hurford and Green (1982), Gleadow *et al.* (1986), Laslett *et al.* (1987), Green (1989), Green *et al.* (1989) and Brown *et al.* (1994).

The apatite samples yielded two distinct populations each exhibiting a specific cooling pattern. Each, therefore, required separate interpretation (details in Gunnell *et al.*, in preparation; Gunnell and Fleitout, 1998). Briefly, a first set of highly consistent results involved the samples collected on the backslope of the Western Ghats, where slow, monotonous cooling is observed throughout the Mesozoic, though possibly accelerated in the Tertiary. Using current geothermal gradients given in Verma (1991) for the Dharwar craton, values between 8 and 11°C km^{-1} provide mean denudation rates over the crystalline basement of *c.* 15–20 m Ma^{-1} in the Mesozoic. These were sustained and, possibly, increased in the Cenozoic though the fission track data do not provide direct information on this aspect (Gunnell, 1998). The use of present-day heat flow values is justified from the understanding that the Dharwar craton has been stable since the Palaeozoic at least, and that the Reunion plume shows no sign of having reheated the upper continental crust to the point of annealing sample fission tracks.

The second set of samples, collected along the Western Ghats foreland, reveals a fairly consistent, mid-Tertiary *acceleration* in the rate of cooling which is not observed on the backslope of the Ghats; it follows an initial phase of slow cooling which resembles the cooling rates in the backslope region. The acceleration at

31±11 Ma, approximately 30 Ma after the recorded rifting and flood basalt event at *c.* 60–65 Ma, occurs very late after the peak of tectonic activity. It is therefore doubtful whether it should at all be interpreted as a direct response of the denudation system to the new Arabian Sea base level. Indeed, in other rifted margin regions studied by fission track analysis, such as the Red Sea, the erosional signal subsequent to tectonic relief generation registers within 5 to 20 Ma (Van der Beek, 1995). The acceleration in denudation in the Oligocene must then be taken as an indication of some other causative event. Possibilities are discussed below.

MODELLING OPTIONS AND EQUIFINALITY IN GEOMORPHOLOGY

Rift-flank denudation may theoretically conform to two major patterns of evolution. These provide an illustration of equifinality in geomorphology.

(i) In the first scenario, the initial rifted margin creates a new drainage divide and the system evolves by parallel scarp retreat. This model was implemented by Gunnell and Fleitout (1998) in a companion paper which showed that scarp retreat would also lead to an *amplification* of initial escarpment relief.

(ii) In the second scenario, the pre-rift drainage divide is located some distance inland from the initial rift boundary at the time of rifting (Figure 3). Rapid erosion removes the mass of crust seaward of the original drainage divide by downwearing and eventually creates a steep escarpment in the vicinity of the drainage divide.

Interestingly, the fission track results for the samples collected in the Kanara lowlands (Gunnell *et al.*, in preparation), located seaward of the escarpment, are open to either of the two interpretations. The sudden acceleration in cooling rates, which took place some 30 Ma after the passage of the Reunion plume, can be taken as an indication of several possible events. We considered the following.

(i) Some authors (Kalaswad *et al.*, 1993) argued that the rifting event occurred some 250–300 km to the east of the present coastline, between Madagascar and the Laccadive microcontinent, which could explain that no clear-cut signature of the official rifting event was registered in the fission track record of mainland India. It seems, however, unrealistic to presume that the initial continent margin retreated, from somewhere west of the Laccadives, by several hundred kilometres in Cenozoic times. Known rates of scarp recession, compiled by Kukal (1990) or Goudie (1995), do not exceed averages of 1–2 km Ma^{-1}, though more extreme exceptions are reported in relation to particularly soft rock (e.g. Steckler and Omar, 1994). Widdowson and Cox (1996), restricting their analysis to the Deccan trap region, also favoured this solution by assuming that the present-day shelf edge (which, they speculated, lies 100–200 km offshore) marks the initial position of the escarpment. This would amount to an average retreat rate of 2–3 km Ma^{-1}. In truth, however, the Indian shelf edge lies 250–300 km off the Maharashtra coast and narrows progressively to *c.* 60 km off the coast of Kerala. Since the present-day Ghats escarpment is nevertheless coast-parallel and continuous (Widdowson and Gunnell, in press), it should logically imply that retreat rates were three to four times higher in the Bombay basalt region than in the Kerala granulite terrain. Although this may indeed be a theoretical possibility, supported by the fact that offshore sediment volumes are larger in the Bombay basin than in the Kerala basin (Figure 2), other options deserve to be examined.

(ii) Another, though less likely, cause is that the accelerated cooling is not a manifestation of denudation, but of a drop in heat flow attributed to the decay of basal heating of the lithosphere by the Reunion plume. This hypothesis is untenable for the reason that Mesozoic cooling trends of the upper crust appeared initially unperturbed by the presence of the plume, and that denudation is necessary to account for the substantial discharge of terrigenous sediment in the offshore basins in the Neogene (e.g. Whiting *et al.*, 1994).

(iii) A further possibility is to suppose that the initial relief of the Indian margin, unlike other high-elevation rifted margins such as South Africa, Arabia or the Transantarctic Mountains, was a fairly low-elevation rifted margin, with the initial fault scarp located somewhere quite close to the present-day coastline. This possibility was examined in greater detail by Gunnell and Fleitout (1998), who suggested that cooling

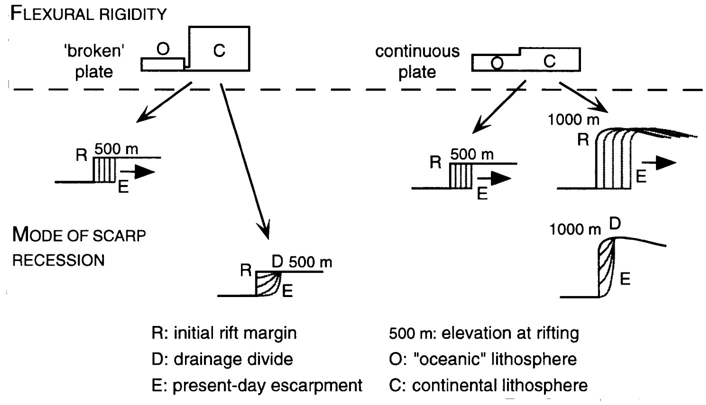

Figure 3. Conceptual depiction of elastic plate and scarp recession scenarios explored in this paper. In each case, three arbitrary, intermediate stages of recession are illustrated. The 'broken' plate scenario represents, in fact, a continuous plate with an extremely weak (though non-zero) transition between the unstretched continental and shelf/oceanic lithospheres (cf. Figure 4; see also Gunnell and Fleitout, 1998)

rates remained surprisingly modest for up to 30 Ma after the rifting event because fission tracks cannot resolve weak denudational signals. These are expected when available relief remains inferior to about 500 m. If this assumption is correct, the post-Oligocene acceleration in denudation is consistent with the pediplanation principle imagined by King (1995), where an isostatic response occurs only when a lateral threshold of unloading from the edge of the continent has been exceeded. It does not, however, subscribe to King's belief that the threshold distance of headward erosion into the continent before rebound occurs should attain 500 km (see reasons given in (i)). A West Coast Fault, though contested by some (review in Chandrasekharam, 1985), has long been held by geologists to locate the initial fault scarp, and is usually (though varyingly) mapped close to the current coastline. In the Bombay region, new evidence (Dessai and Bertrand, 1995) of *onshore* coastal faulting provides ground for rekindling the debate on the relative role of faulting and flexure in the uplift of the Western Ghats. Overall, this hypothesis concurs with the parallel scarp retreat model, where escarpment and drainage divide coincide from the outset.

(iv) Also consistent with the accelerated cooling of post-Oligocene times, a final hypothesis considers that the present-day position of the Western Ghats escarpment is not strictly a consequence of parallel scarp retreat, but rather the result of downwasting of the Deccan plateau edge by west-flowing rivers which, since the time of rifting, had their headwaters located inland of the rift flank (Figure 3). In this particular case, the evolution of the margin since rifting can be viewed as comprising two major stages. Initially, the west-flowing rivers, while catching up with their new base level, breach the rift flank. This phase is therefore dominated by linear stream downcutting, which may account for the persistence of slow areal denudation reflected in the fission track record. In a second phase, divides between the entrenched canyons waste away, with the final outcome resulting in a steep escarpment, newly located close to the former drainage divide. This second phase concurs with the accelerated Neogene denudation reflected in the offshore sediment and onshore fission track records. It does not quantitatively modify the global mass balance of the parallel scarp retreat model, but offers a qualitatively alternative pathway of landscape development which has been proposed for the Atlantic margins of Africa and southeastern Australia (e.g. Summerfield, 1991a).

This speculative pattern of evolution, however, warrants two important prerequisites. The first is that the initial watershed was effectively positioned inland from the rift flank; although it can be assumed that the Reunion plume created a pre-rift shoulder to which the drainage divide conformed, thereby vindicating an active rather than a passive rifting scenario, this remains difficult to prove in India. Secondly, it is necessary that the drainage divide does not shift excessively during landscape evolution: indeed, if indefinite stream head recession into the Deccan plateau accompanies the first phase of escarpment breaching, scarp steepening during the second stage is unlikely to occur. The success of this

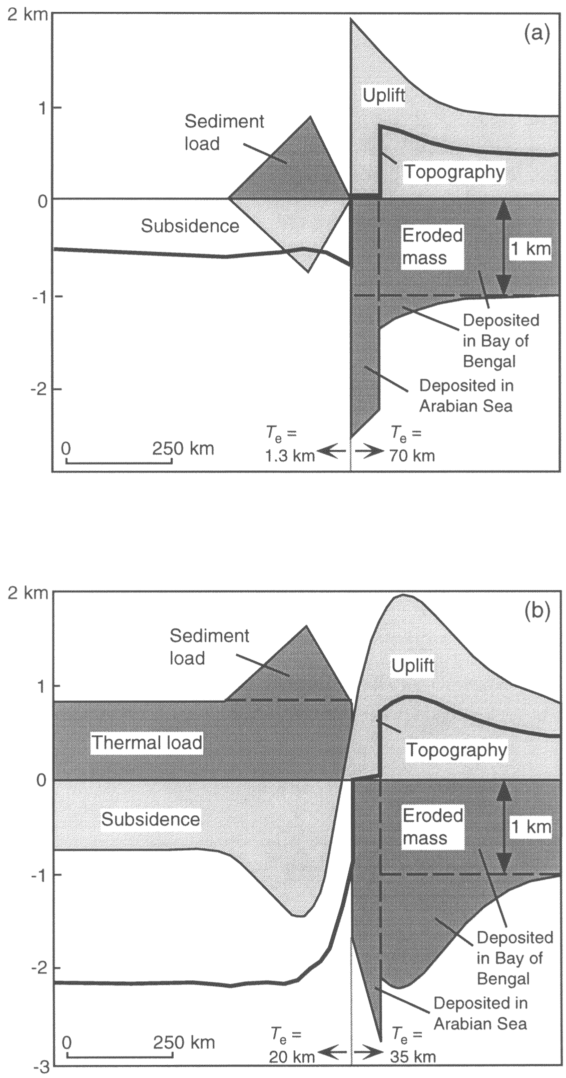

Figure 4. Modelled erosional unloading and tectonic uplift. Model topography is shown in the context of (a) a 'broken' elastic plate and (b) a continuous elastic plate with bimodal elastic thickness. Contact between elastic thickness values across the margin is purely mechanical in nature, and is not assumed to represent the physical contact between ocean and continent. In other words, short of knowing the exact geophysical attributes of the offshore lithospheric structures, the rigidities of oceanic, 'intermediate' and/or stretched continental lithospheres are considered to be equivalent

form of evolution then relies heavily on the presence of structural barriers in the craton, *already effective at 60 Ma*, having obstructed the migration of the divide during the Cenozoic. This possibility is not ruled out for parts of the escarpment located in Kerala (not detailed in this study), but there is little evidence in the region of interest, or indeed in the neighbouring Deccan trap province (Widdowson and Gunnell, in press), to indicate that structural predesign has controlled rift-flank drainage in such a generalized manner.

The passive rifting (where subsidence precedes eventual shoulder uplift) and active rifting (where domal uplift precedes rifting) alternatives were tested using computer simulation, and the relative importance of denudation in generating the expected shoulder uplift is discussed below.

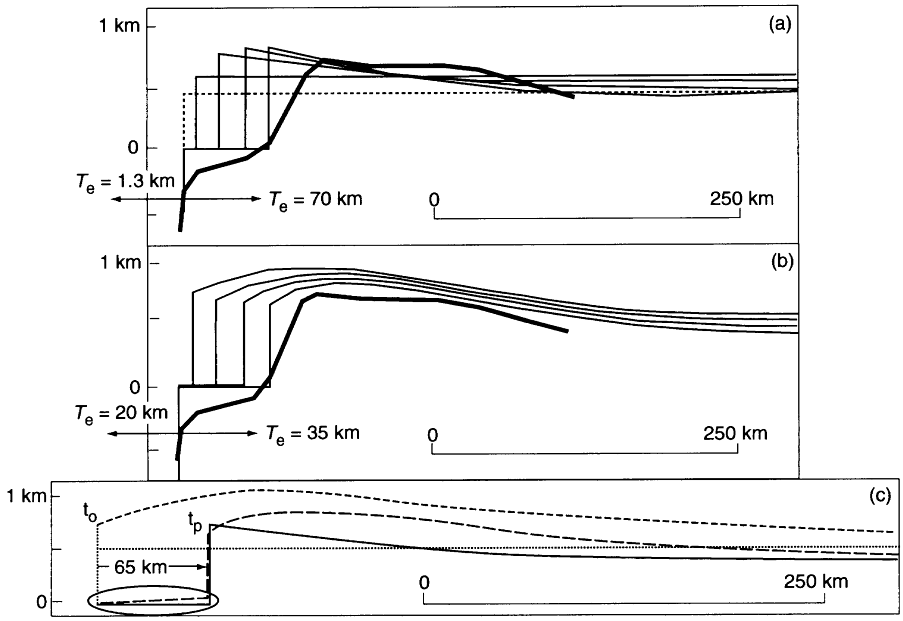

Figure 5. Two ways of achieving a topographic shoulder by rifting and 65 km of scarp retreat: (a) flat-lying Cretaceous palaeosurface progressively uplifted by denudational rebound with minimal (non-zero) coupling with offshore lithosphere; (b) initial 1 km high, plume-related shoulder, with greater degree of coupling between onshore and offshore, subjected to decay over time; (c) synthesis of (a) and (b) showing initial (t_0) and present-day (t_p) conditions. Note substantial differences in T_e for each scenario and difference in natural slope of escarpment foreland (encircled). In each case, four stages of scarp retreat are represented

MODELLING RESULTS

Gunnell and Fleitout (1998) examined the consequences of erosion on the Western Ghats shoulder morphology by varying denudation patterns in the Deccan interior while keeping sediment delivery to the Arabian Sea constant. A finite difference computer model simulated, for different input values of lithospheric flexural rigidity, the shoulder uplift which is believed to have proceeded during the course of the Tertiary. It was tentatively concluded that the present-day shoulder morphology is best generated by stripping a thickness of 1 km off the entire Dharwar craton, and by assuming a high elastic thickness, in excess of 70 km, for the onshore Deccan lithosphere. The model, however, performed satisfactorily only in the case of an elastic plate with minimal coupling between the continent and the margin (Figure 3, 4a and 5a), i.e. a virtually ‘broken’ plate suggesting a very weak lithosphere in the continental shelf or hinge zone. The assumed weakness of the offshore crust was attributed to the intense faulting mentioned in the literature. Total Cenozoic surface uplift was close to 300 m. For the sake of comparison, Gilchrist and Summerfield (1990) estimated 600 m of surface uplift since the Cretaceous for the South African passive margin shoulder relative to the cratonic interior, although with a modelled elastic thickness of only 15 km.

The model simulation behaves in the following way: from an initial rift margin at $t_0 = 60$ Ma (located offshore), with a relief of 500 m and a flat-topped Deccan palaeosurface, the escarpment retreats away from the initial rift margin, while discharging step-wise the mass of crustal material now found as sediment on the continental shelf. The offshore basin simultaneously subsides under the load of incoming sediment. Meanwhile, the backslope is also progressively stripped by increments. The erosion law governing the denudation processes both in the uplands and on the foreland was chosen to be proportional to the relative relief between the elevation reached at the iteration of interest and the initial elevation at t_0 (e.g. Summerfield, 1991b). This reference level is, to the west of the retreating escarpment, 0 m (average sea level, supposed unchanged), and to the east, on the uplifting plateau surface, 500 m. Since the relative relief on the seaward side at t_0 is 500 m while being zero in the hinterland, the rate of erosion in the coastal region remains from the start proportionately

higher than on the backslope, an asymmetry which deliberately contributes to maintain elevations in the coastal foreland realistically close to sea level while, at the same time, providing a cause to explain the permanence of rifted margin relief at geological timescales.

Flexural rigidity (D) and effective elastic thickness (T_e) are given by the relation:

$$D = \frac{ET_e^3}{12(1-v^2)}$$

and

$$T_e = \sqrt[3]{\frac{12(1-v^2)D}{E}}$$

where E is Young's modulus and v is the Poisson coefficient.

The competing alternative to the discontinuous plate model assumed a continuous elastic plate (Figure 3), but failed to yield a satisfactory fit if denudational unloading was held to be the sole cause of uplift. It can be concluded that, in a context of passive rifting, a strong degree of coupling between the continent and the margin requires, in addition to denudation, another factor of lithospheric buoyancy, such as underplating, to produce an adequate shoulder topography.

One way of avoiding this problem, which is specifically related to the continuous plate model, is to consider that the continental freeboard upon rifting was greater than the previously postulated 500 m and that a topographic swell existed from the start. From the sole point of view of modelling, the question as to whether the swell is thermal or petrological (underplate) is not considered. Thus, assuming this time an elevation of 1000 m at t_0 (using, for instance, the Red Sea rift as an arbitrary analogue), the present-day shoulder morphology can be achieved with a continental T_e of 35 km (Figures 4b and 5b). The stretching factor (McKenzie, 1978) is assumed from petrological data to be $\beta = 2$ (i.e. the crust is stretched by 50 per cent; Ellam, 1992; Peng and Mahoney, 1995), therefore generating an additional 1·5 km of offshore thermal subsidence to the sediment-driven subsidence in the semi-infinite plate model.

Cenozoic escarpment evolution reveals parallel retreat accompanied, in reverse to the semi-infinite plate model where escarpment relief *amplifies* over time, by a gradual *reduction* of relief (Figures 5b, 6a and 6b). Significantly, the role of denudation in the foreland in achieving a shoulder morphology after 60 Ma when an initial (thermal?) shoulder already exists is negligible, as illustrated in Figure 6c, where denudation in the escarpment foreland was deliberately set to zero throughout the simulation run. Even more interestingly, however, it is revealed that when denudation is negligible, offshore subsidence induces, through the mechanical coupling inherent to a continuous elastic sheet, a greater degree of progressive inland migration of the flexural bulge than when erosion is introduced. The modelling therefore suggests that erosion, while not generating the bulge itself, has a stabilizing effect on landward shoulder migration. However, it was also found (not illustrated) that the higher the value of T_e, the further inland the geographical location of the flexural shoulder: to avoid having the Western Ghats rise too far in the centre of the Indian subcontinent, the continuous plate model therefore imposes 35–40 km as an upper limit to elastic thickness. This is considerably less than the 100 km postulated for the Deccan in other modelling studies (e.g. Watts and Cox, 1989).

In spite of the greater available relief of the escarpment at the outset, the delay in the fission track denudation signal could then be explained by the 'drainage divide hypothesis' which assumes, in spite of any verified structural controls on drainage patterns at the K/T boundary, that uplift preceded rifting.

If we now focus specifically on the implications of denudational rebound on the morphology of the Western Ghats foreland, leaving aside the backslope uplands, it appears that the terrain exhibits two specific features: (i) a general tilt away from the escarpment, in the form of (ii) two distinct lateritized 'pediment' levels (Widdowson and Gunnell, in press). The question arises as to whether the observed slope is caused by tectonic

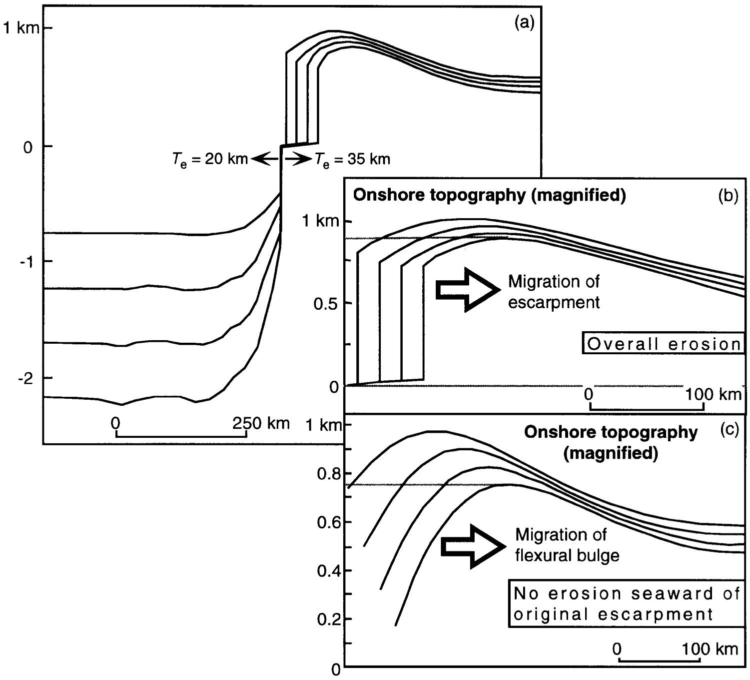

Figure 6. The role of erosion in controlling migration of the topographic bulge towards the continent interior in a continuous plate scenario. Horizontal scale is compressed by comparison with Figure 4

tilting alone (Figure 5c) or whether it is at least partly a result of geomorphologically controlled pediment formation, and whether the stair-like topography is caused by staccatoed denudational rebound or by some other factor.

Firstly, the slope itself requires an explanation: in the context of a continuous elastic plate with decreasing seaward rigidity, modelling results (Figures 4b and 5b) suggest a monoclinal flexure or camber, reminiscent of the Lebombo monocline of southeastern Africa, thereby vindicating a tectonic origin for the observed seaward slope. Meanwhile, the 'broken' plate yields a concave-up, cantilever effect, for which the seaward slope of the foreland needs to be accounted for by pedimentation processes (Figure 5c). It has been shown (Widdowson and Cox, 1996; Widdowson, 1997), by a method of geochemical fingerprinting of basalt formations, that the Deccan traps exhibit a gentle monoclinal dip from the escarpment ridge towards the coast. This downwarp is clearly evident in the Bombay region (the 'Panvel flexure'), where discrete rotational block faulting (which affects the dip of coastal flows) may have exaggerated the flexural effect (Dessai and Bertrand, 1995), and suggests that the unconformable volcanic sequence was affected by a flexural deformation of the underlying basement in post-eruptive Tertiary times. If such an interpretation is correct, then it is reasonable to assume that the Dharwar craton further south, which lacks stratigraphic evidence, is also affected by what should be a continuation of the observed monocline and its two levels of lateritic pediment ramps. The continuous plate model appears to vindicate this seaward monoclinal bend, and the sloping foreland pediment surface is portrayed as being a primary, tectonic feature. Predictably, it also satisfies the identification of seaward-dipping offshore seismic reflectors (Hinz, 1981), interpreted to be the continuation of basalt flows. The monoclinal deformation of the lava pile is the result of the post-rift subsidence of the margin, and is therefore a consequence of the continuity of the modelled plate.

Secondly, the sloping topography is two-tiered: Stüwe (1991), in a flexural modelling exercise comparable to the one presented here, argued that stair-like topography at the foot of major escarpments, such as described by King (1955) in southern Africa could be entirely explained by incremental flexural rebound forces, whether the elastic plate was continuous or broken, due to an intrinsically non-linear relationship between scarp migration distance and plate uplift. The author thereby vindicated the cyclicity of escarpment foreland landscapes by the

cyclicity of elastic rebound in the context of a retreating escarpment. In an independent discussion, Gilchrist and Summerfield (1991) expressed the divergent opinion that the physics of lithospheric flexure actually imply that denudational rebound is a *continuous* process which cannot, therefore, allow erosion cycles to leave their hallmark on the landscape.

Clearly, in the case of a 'broken' plate, the cyclicity of rebound can be explained by a hypothetical stick-slip motion of the plate margin during its denudational rebound history. In the case of a continuous plate, however, the limiting factor would be the total distance of escarpment retreat: for limited retreat distances, rebound is insufficient and the predicted shoulder effect will not match the observed topography; for much greater distances of scarp recession, the predicted match is theoretically more satisfactory. However, large (100–300 km) distances of scarp recession imply amounts of Cenozoic denudation which far exceed the known volumes of post-volcanic offshore sediment – especially in the case of active rifting, where volcanism is supposed to precede rifting. Therefore, while the onshore structure and morphology of the margin can, in theory, be achieved by the unloading of a continuous elastic sheet, the physical causes and specific boundary conditions remain controversial. It may be that the step-like topography is due to rejuvenation caused by eustatic changes and that the overall slope alone is tectonically determined, in which case the theory presented by Gilchrist and Summerfield is more realistic.

CONCLUSION

As the foregoing discussion points out, simulation modelling in the Earth sciences contributes to selecting better solutions from among a list of reasonable possibilities. However, a residuum of non-uniqueness often persists. Bishop and Brown (1992), for example, in a geomorphological study of the Lachlan Valley region of New South Wales, found difficulty in discriminating between three solutions to account for Cenozoic landscape development: isostatic rebound of an infinite elastic plate of low flexural rigidity, flexural rebound of a thicker but faulted plate, or even a visco-elastic rather than purely elastic lithospheric response were hypothesized and established to yield similar outcomes. Modelling therefore may not perform as highly as to challenge equifinality in the physical environment, but it helps to narrow the gap between empirical observation and theory.

The model illustrated in the present study does not reject the possibility that the shoulder uplift of the Western Ghats was achieved during the Tertiary through tectonic uplift caused by Earth interior processes. This possibility is suggested by the infinite plate model for an assumed initial plateau elevation of 500 m and parallel scarp retreat, where the very low component of rebound needs to be supplemented by another cause of uplift, the exact nature of which still remains to be firmly established (underplating is a possible candidate). For an assumed initial (thermal?) shoulder elevation of 1000 m and a drainage divide maintained inland from the primitive rift flank, a coastal monocline is obtained, although flexural rigidities need to remain low (≤35 km) to allow for sufficient surface uplift. More simply (Occam's razor), a third alternative suggests that the shoulder effect can be accounted for by denudational unloading and flexural rebound alone if a mechanically very weak offshore region (Figure 3) is conceded (cf. Gunnell and Fleitout, 1998). If such is the case, the Western Ghats passive margin landscape provides a challenging example of first-order landforms, traditionally attributed to geophysical processes, being features of the Earth's surface governed by the geographical distribution pattern of long-term denudation and perpetuated by flexural rebound. Nevertheless, each of the examined possibilities has its own drawbacks due to unverifiable speculations concerning boundary conditions.

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